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Unsteady Aerodynamic Models for Flight Control of Agile Micro Air Vehicles

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- **Background**
  - **Objective**: obtain models for unsteady aerodynamics of fixed-wing MAVs (e.g. incorporating dynamic stall, vortex shedding)
  - **Technical approach**: systematic models using approximate balanced truncation (balanced POD); empirical, phenomenological models that capture correct bifurcation behavior
  - Contributors: Steve Brunton, Zhanhua Ma (Princeton); T. Colonius (Caltech)
- **Technical progress to date**
  - Obtained phenomenological models that capture unsteady behavior over a large range of angle of attack
  - Theoretical framework for balanced POD about periodic orbits (e.g. vortex shedding)
  - Current work: include forcing terms to avoid the need to tune initial conditions
- **Impact:** Models will enable control design for robust performance of MAVs during agile maneuvers, severe gusts
- **Future plans:** models for dynamically pitching/heaving airfoils
- **Collaboration opportunities:** Michael Ol, AFRL/VAAA

- **Objectives**
  - Obtain models for unsteady aerodynamics of fixed-wing MAVs, for robust control during rapid maneuvers or severe gusts
- **Previous work**
  - Vast majority of previous models are quasi-steady (e.g. $CL(\alpha)$)
  - Linear models of dynamic stall (Goman 1994, Magill 2003)
  - Nonlinear models for unsteady aerodynamics on a rolling delta wing (Myatt 1996, Allwine 2004)
- **Two modeling approaches pursued here**
  - **Systematic:** approximate balanced truncation (balanced POD) for model reduction of Navier-Stokes, for pitching and/or heaving wings
  - **Phenomenological:** simple models obtained without using Navier-Stokes
- **Collaborations / Acknowledgments**
  - Steve Brunton, Zhanhua Ma (PU grad students)

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- Caltech MURI team, especially Tim Colonius, Sam Taira

Coherent structures about a rapidly pitched airfoil

- **Direct Numerical Simulation of flow over a flat plate**
  - Immersed boundary solver (Colonius & Taira 2006, 2007)
  - Compute unsteady loads at fixed angle-of-attack, and pitching/heaving
  - Lagrangian Coherent Structures (LCS) identify boundaries of separation bubbles, leading-edge vortices: important features to model

Coherent structures about a stationary airfoil

- Lagrangian Coherent Structures determine boundaries between qualitatively different regions (e.g., separation bubble boundary)
  - LCS are ridges of Finite-Time Lyapunov Exponent field

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Nonlinear models valid near the bifurcation point

- **Phenomenological model**
  - Numerical continuation [Ahuja and Rowley, 2007] reveals a Hopf bifurcation as angle of attack increases
  - Construct a nonlinear model as the *normal form* of the Hopf bifurcation:
  - By construction, model captures correct nonlinear behavior. Calibrate constants against simulation data.

Nonlinear models valid near the bifurcation point

- **Model comparison with DNS** (Re = 100)

Systematic models: Balanced POD

- **Model reduction for very large systems**
  - **POD** has limitations (low-energy features often dynamically important)
  - **Balanced truncation**: good error bounds for linear systems, but not computationally tractable for very large system dimension (e.g. fluids)
  - **Solution**: empirical Gramians [Lall et al 1999], algorithm for computing balancing transformation without computing the Gramians themselves [Rowley 2005]
  - Method involves impulse responses of linearized and adjoint systems

Systematic models: Balanced POD

- **Balanced truncation produces excellent models, but is computationally intensive for very large systems**
  - Cannot even store the whole Gramians or balancing transformation: square matrices, dim > 105
  - Interested only in the leading columns/rows of the balancing transformation and its inverse:
  - Columns of Φ1 are *balancing modes*; columns of Ψ1 are *adjoint modes*
- **Compute these directly from snapshots of the linearized and adjoint systems**

Balanced POD for periodic systems

- **Periodic orbits often arise in fluids**
  - Periodic vortex shedding
  - Flow control: open-loop forcing at a single frequency
- Standard balanced POD works for linearizations about an **equilibrium**
- **Desire reduced-order models valid near a periodic orbit**
  - Main idea is to lift the time-periodic system to a time-invariant system with many more inputs and outputs, then apply standard BPOD procedure
    - Subtleties: whether to use several different output projections (a different projection at each step around the periodic orbit) or the same projection at each step

Impact

- **Air Force impact**
  - Unsteady effects unavoidable for Micro Air Vehicles
    - Agile maneuvers: time scales of vehicle dynamics commensurate with time scales of flow structures
  - Quasi-steady models may drastically underestimate/overestimate lift/drag/moments
  - Disturbances (gusts) typically large; require good models for robust control
- **Direct impacts**
  - Improved aerodynamic models for robust control of fixed-wing MAVs
- **Indirect impacts**
  - Development of systematic reduced-order modeling techniques useful for other control problems (e.g. flow control, design optimization, flapping-wing flight)

Future Plans

- **Phenomenological models**
  - Introduce coupling terms to avoid the need to tune initial conditions for a particular angle-of-attack
  - Test models against simulations with pitch/plunge, improve models as necessary
  - Use more realistic airfoil (SD7003)
- **Systematic models**

    - Implement Balanced POD for models linearized about an equilibrium; linearized about a periodic orbit; scheduled linear models; and full nonlinear models
- **3-dimensional effects**
    - Characterize differences between 2d
    - Adapt phenomenological models as needed.
- **Comparison with experiments**
    - Michael Ol plunging airfoil experiment?

Collaboration Opportunities

- **Michael Ol (AFRL/VA)**
    - Experiments on plunging SD7003 airfoil
    - Leading AIAA Low-Reynolds-number discussion group
- **Miguel Visbal (AFRL/VA)**
    - High-fidelity numerical simulations of laminar separation bubbles
- **Johnny Evers (AFRL/MN)**
    - Autonomous MAV flight; closed-loop control